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Geometrical Aspects of Dielectric Charging

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Abstract

The electrostatic field in a dielectric layer, which is in contact with a conducting electrode, is considered. It is shown that the geometrical nature of contact causes a considerable local amplification of the electrostatic field. This provides insight, and explains why dielectric charging occurs even when the nominal electrostatic fields seems to be relatively low in amplitude. The analysis also demonstrates why a constant and uniform electrostatic loading induces dielectric charging with alternating polarity in different locations in the dielectric.

Keywords: Dielectric Charging, Stiction.

1. Introduction

Dielectric charging is a failure mechanism that dominates the reliability of capacitive RF-MEMS switches [1]. This phenomenon has been intensively investigated in recent years. Much experimental effort has been invested in finding actuation schemes that would delay failure caused by dielectric charging [2,3]. Recent studies showed that spatial variations in dielectric charging cause lock-down of the switch [4,5]. However, the exact mechanism that results in spatial variation of dielectric charging is yet unclear. The present study aims to provide insight, and proposes a mechanism that explains why a constant and uniform electrostatic loading of a capacitive switch induces spatial variations of dielectric charging.

2. Dielectric-conductor contact

2.1. Dielectric-conductor interface

A capacitive RF-MEMS switch is illustrated in Fig. 1a. A grounded conducting deformable bridge is constructed above a fixed driving electrode which is coated by a thin layer of dielectric. The fixed conducting electrode is the line in a co-planar waveguide (CPW) which carries the RF signal [6]. The suspended bridge may be pulled down into contact with the dielectric layer by superposing a pull-in dc voltage to the line electrode. The actuation voltage

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is designed to be larger than the RF signal to prevent unintended actuation [7]. In any case, once the bridge is pulled down, the actuation voltage may be reduced to the hold-down voltage to reduce the electrostatic stress across the dielectric.

The focus of this investigation is the electrostatic stress across the dielectric layer in the *down-state* of the capacitive RF-MEMS switch. The effect of electrostatic stress on dielectric charging at contacting and non-contacting interface asperities, are of specific interest.

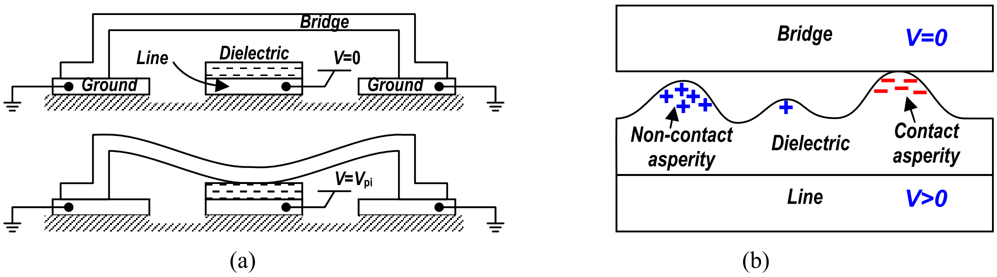


Fig. 1. (a) Schematic view of a capacitive RF-MEMS switch. A dc bias on the line electrode pulls the grounded conductive switch into contact with the dielectric. The increase in capacitance shunts the RF signal to ground. (b) Close-up view of the rough interface between the dielectric and bridge conductor. Only a few dielectric asperities are in actual contact with the bridge electrode.

It is assumed that the dielectric layer is perfectly attached to the underlying line electrode. In contrast, the interface between the dielectric layer and contacting conductive bridge is far from perfect. Both the top surface of the dielectric layer and the bottom surface of the grounded electrode are not perfectly flat. Without loss of generality, the interface may be considered as a contact between a non-flat dielectric layer and a perfectly flat conductive layer. In this way the roughness of both surfaces are loaded as an effective roughness of the model dielectric (Fig. 1b).

2.2. Asperity model

In this work we model asperities as ideal axi-symmetric rises in the surface and consider a single asperity at the center of a cylindrical representative cell of dielectric (Fig. 2). The surface of the asperity is given by a simple 3rd order Bezier curve

$$d(r) = d_0 - g_a - h_a \frac{r^2}{R_c^{\,2}}\left(3 - 2\frac{r}{R_c}\right) \qquad (1)$$

Here $d(r)$ is the thickness of the dielectric, r is the radial distance from the asperity peak, g_a is the gap between the dielectric asperity peak and bridge in the down-state, h_a is the height of the asperity, and R_c is the radius of the axi-symmetric representative cell. Only asperities for which g_a=0, are in actual contact with the bridge.

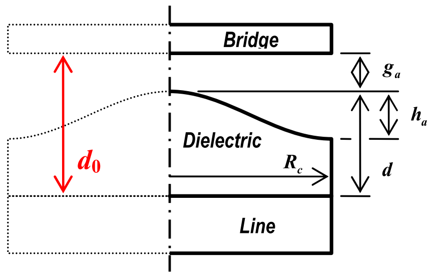


Fig. 2. Schematic view of a capacitive RF-MEMS switch. A dc bias on the line electrode pulls the grounded conductive switch into contact with the dielectric. The increase in capacitance shunts the RF signal to ground.

The arbitrary asperity profile (1) is considered because it is easy to implement in finite elements simulations. The exact functional form of the asperity is not important. As will be shown in the following, what is important is the fact that at the vicinity of contact points, the asperities are spherical. The crack-like air gap surrounding contact points strongly affects the electrostatic stress at the interface.

2.3. Simplified analytic solution

As a first step, it is constructive to consider a simplified model of the problem. In this simplification it is assumed that the electrostatic field between the fixed line electrode and the pulled-down bridge electrode is purely vertical (i.e. normal to the line and bridge electrodes). This assumption fails to describe the exact electrostatic field when the dielectric thickness is non-uniform. Nevertheless, the solution obtained is simple to derive, and gives insight to the electrostatic stress in the dielectric.

From the assumption that the field is purely vertical it follows that the local capacitance (per unit area) and the electrostatic field are given by

$$c(r)=\frac{\varepsilon_0}{d_0}\frac{1}{\varepsilon_r\dfrac{d(r)}{d_0}+1-\dfrac{d(r)}{d_0}},\qquad E(y)=\begin{cases}\dfrac{V}{d(r)+\varepsilon_r\left(d_0-d(r)\right)} & 0\le y\le d(r)\\[2ex] \dfrac{\varepsilon_r V}{d(r)+\varepsilon_r\left(d_0-d(r)\right)} & d(r)\le y\le d_0\end{cases}\qquad (2a,b)$$

Here V is the voltage difference between the line and pulled-down bridge.

The voltage and field are presented in Fig. 3a for g_a=0, h_a/d_0=0.2 and ε_r=5. At the point of contact (i.e. r=0, y=d_0) the dielectric material fills the entire gap between the line and bridge electrodes. Therefore the electrostatic field in the dielectric is E=V/d_0. In the vicinity of that contact point (i.e. r→0), the dielectric fills most of the gap but an infinitesimal air gap separates the bridge form the dielectric. Nevertheless, the dielectric dominates the local capacitance and therefore the field in the dielectric is only slightly below its maximal value E=V/d_0. However, due to continuity in dielectric displacement across the interface between the dielectric and air, it follows that the amplitude of the electrostatic filed in the 'crack-like' air gap is ε_r times larger than in the dielectric (marked as *Contact point* in Fig. 3a). The electrostatic field at the tip of the dielectric asperity is amplified due to geometry.

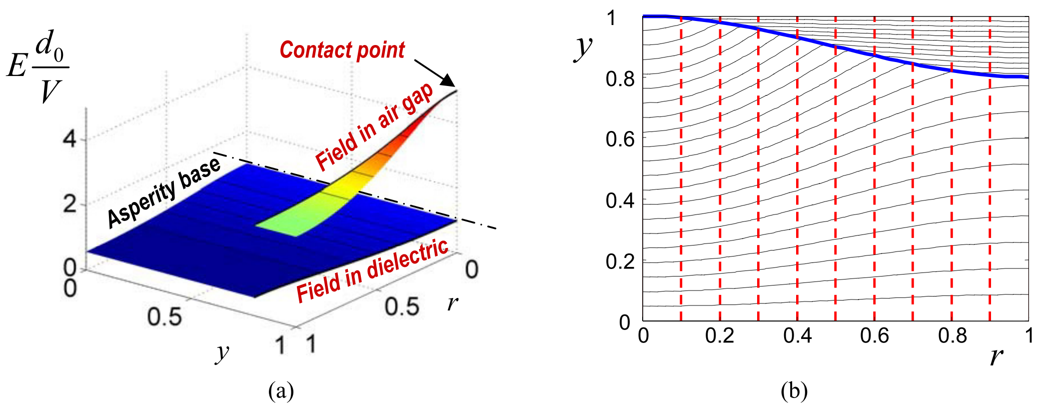


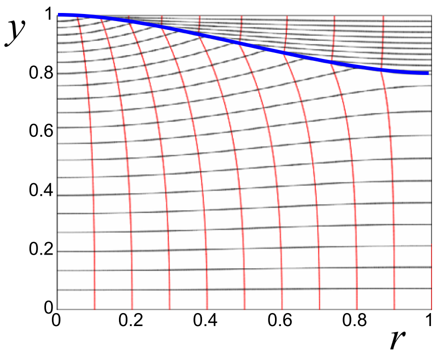
Fig. 3. (a) Electrostatic field obtained by the simplified model (for g_a=0, h_a/d_0=0.2 and ε_r=5). (b) In the simplified model, the field lines are assumed to be vertical. However, the voltage contours obtained from the simplified solution are not orthogonal to the field lines.

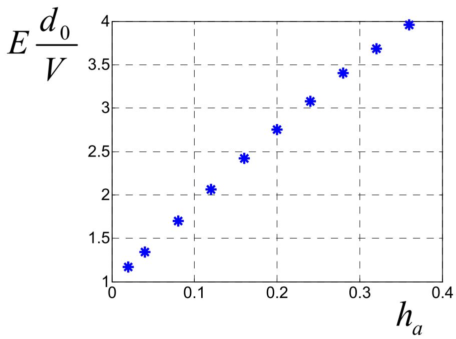
The simplified analytic solution assumes that the electrostatic field is normal to the electrodes (vertical dashed lines in Fig. 3b). However, the voltage contour lines (solid curves in Fig. 3b) are not orthogonal to the field lines, which means that the assumption is incompatible with the exact solution of the problem.

2.4. Finite-elements simulation

The same electrostatic problem was solved by COMSOL 3.5, using cubic triangular elements and three levels of mesh adaptations. The solution for a specific problem with g_a=0, h_a/d_0=0.2 and ε_r=5 is presented in Fig. 4. In this solution the field lines and voltage contours are indeed orthogonal at every point. The convergence of field lines towards the point of contact at the tip of the asperity means that the electrostatic filed in the dielectric at that point is stronger than $E=V/d_0$. For the specific parameters considered here, the field is in fact $E=2.72V/d_0$. The effect of asperity height on the field amplification is presented in Fig. 4b.

It can be shown that in slightly sharper (and more realistic) asperity geometries, a ten-fold amplification is easily achieved.





(b) (b)

Fig. 4. (a) Electrostatic field obtained by finite elements simulation (for g_a=0, h_a/d_0=0.2 and ε_r=5. (b) The field amplification increases with asperity height

2.5. Spatial variations of injected charge

It is well known that a strong electrostatic field can cause leakage currents in dielectrics. The field reduces the energy barrier in a preferred direction enabling trapped charges to migrate from one trap to another. This is why charge of the same polarity as of the bridge will accumulate at contacting asperities, as schematically illustrated in Fig. 1a. If the asperity is non contacting (same figure), charges with polarity opposite to the bridge will accumulate at the asperity peak, but will not be conducted (shunted) to the bridge due to the air gap. This scenario may explain spatial variations of injected charges in capacitive contacts, that may lead to failure of RF-MEMS switches [4].

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